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Abstract

Unlike other fuels, hydrogen (H_2) can be generated and consumed without generating carbon dioxide (CO_2). This creates both significant engineering challenges and unsurpassed ecological advantages for H_2 as a fuel, while enabling an inexhaustible (closed) global fuel cycle based on the cleanest, most abundant, natural, and elementary substances: H_2, O_2, and H_2O. If generated using light, heat, and/or electrical energy from solar, wind, fission, or (future) fusion power sources, H_2 becomes a versatile, storable, and universal carbonless energy carrier, a necessary element for future global energy system(s) aimed at being free of air and water pollution, CO_2, and other greenhouse gases. The case for hydrogen rests fundamentally on the need to eliminate pollution and *stabilize* Earth's atmosphere and climate system.

Unprecedented Interest in an Old Idea

The "hydrogen economy" is certainly not a new idea. Foreshadowed in 1874 by Jules Verne in *The Mysterious Island* [1], the concept has evolved through society's primary energy transitions, from coal to oil, through the rise of nuclear power, and later to natural gas, wind, and solar energy [2-7]. The basic technologies themselves are well understood. Electrolyzers and fuel cells were invented in the 1800's – before the internal combustion engine or the discovery of oil. Key hydrogen technologies were developed and deployed in the 1960's for the U.S. Space Program. The subsequent oil shocks of the 1970's spurred interest in hydrogen fuel. Many prototype hydrogen automobiles have been built since, alongside research into improving hydrogen production, storage, and utilization.

What *is* new is the unprecedented level of recent public awareness and industry interest in the "hydrogen economy" as a future energy option. This trend accelerated with President Bush's 2003 State of the Union goal of mass produced hydrogen (H_2) cars before 2020, followed by California Governor Schwarzenegger's "Hydrogen Highway" proposal for up to 200 H_2 fuel stations by 2010. The international focus on H_2 has grown sharply in the past 5 years. The raised profile and building momentum of the "Hydrogen Economy" has led to renewed studies [8-10], enthusiasm [11-12], questions [13-14], and notably, criticism from energy and environmental advocates [15-17].

We believe these questions and criticisms can be answered, and that a hydrogen economy is not only justified, but likely a necessary transition for mankind to complete within this century. Consequently, the earlier consensus is reached on this fundamental reality, the sooner technical discussion of the hydrogen economy can move beyond debating pros and cons toward consideration of optimal hydrogen transition timing, and the roles of technological advance and efficient policy to ease and speed deployment.

In this paper we respond to common criticisms of hydrogen fuel, outline the technical challenges, and conclude envisioning a number of hydrogen economy archetypes and the key areas of technical advance required for each.

Common Critiques of Hydrogen Fuel

H_2 has low "well to wheels" fuel cycle efficiency

H_2 is an energy carrier that, like electricity, must be generated from high value fossil, nuclear, or renewable energy sources. Both thermochemical and electrolytic H_2 production processes are typically 60-70% efficient (based on the lower heating value of 120 MJ/kg H_2).

This energetic (and economic) premium often leads to the criticism that hydrogen fuel is less efficient than other approaches to reducing petroleum use or carbon dioxide (CO_2) emissions. For example, hybrid-electric autos using natural gas directly will have higher "well to wheels" fuel economy than hybrid autos using hydrogen generated from natural gas. Similarly, replacing coal-fired power plants with solar, wind, biomass or nuclear electricity will save more carbon emissions than replacing gasoline with hydrogen fuel made by electrolysis from these same sources. These "flat facts" are certainly true, but they are not the whole story.

Electrolysis is commonly characterized as especially inefficient in linear "well to wheels" analyses, since it can involve two conversions: primary energy to electricity *and* electricity to hydrogen. Electrolytic H_2 can nevertheless be attractive from the broader perspective of an energy *system*. Early in the transition to hydrogen, distributed electrolysis of hydrogen at small scales, coupled to water or space heating (analogous to combined heat and power) could improve system energy efficiency substantially and concentrate CO_2 and other emissions into large point sources (i.e. power plants) feasible for capture and geologic sequestration. In the future, low or zero carbon utilities with high levels of solar, wind, and nuclear power in the generation mix, will of necessity have excess off-peak electricity for electrolysis. Coupling carbonless utilities with H_2 transportation would reduce or eliminate the need for large amounts of electricity storage, with the attendant energy losses and economic costs, which have so far limited the dispatchability and consequent feasibility of carbonless electricity systems. The ultimate effectiveness of electrolytic hydrogen rests on this strategic question: how viable can future carbonless electricity systems (e.g., wind, solar, and nuclear) be on a global scale without a large, flexible load (i.e. electrolysis)?

If made from fossil fuels, hydrogen can be produced thermochemically (e.g. coal gasification or steam methane reforming), with greater efficiency than electricity or likely any other fuel (e.g., synthetic natural gas, methanol), due to its ubiquitous precursor (water) and unique molecular simplicity. Fossil-fueled hydrogen production and/or fuel cell cogeneration of electricity would further improve overall system efficiency by avoiding dilution of CO_2 exhaust streams with atmospheric N_2, should CO_2 capture and geologic sequestration ultimately prove viable. Given economic centralized CO_2 capture and sequestration, pipelined H_2 generated from coal can efficiently displace distributed fossil fuel end-uses (e.g. residential fuel cells for combined heat and power) sharing infrastructure with H_2 for transportation fuel.

Finally while it is true that significant energy (10-30% of its fuel value) can be required to compress and/or liquefy hydrogen for distribution or storage onboard vehicles, this energy can be at least partially recouped by designing vehicles to take advantage of the additional thermomechanical exergy available in compressed and/or liquid hydrogen (LH_2) to increase power or provide onboard cooling. In the case of aircraft, the much lighter fuel weight of LH_2 is an intrinsic efficiency that compounds with both cruising speed and range.

"Well to wheel" analyses do not typically examine more symbiotic energy system options (combined heat and power, energy storage, sequestration efficiencies, shared infrastructure) like those mentioned above, and are consequently limited in that they do not determine comprehensive energy system efficiencies, or capture temporal variations in both supply and demand (including auxiliary services and coproduction of heat or cooling) as well as storage.

The current electric generation system is a classic example of the limitations of "well to wheels" (or wires) analysis: coal plants are less efficient and require more investment than natural gas combined cycle plants, but still generate electricity at lower cost, while peaking natural gas plants are less efficient and produce costlier electricity than either. Yet, all are necessary components of economically optimal electricity generation systems.

Electric transmission and distribution add a final efficiency conundrum for the H_2 economy, forcing direct current (DC) end-use appliances and devices to convert alternating current (AC). This legacy inefficiency and added cost may become more important as fuel cells, electrolyzers, and photovoltaics, all technologies at the heart of the hydrogen economy, become commodity DC devices. In the final analysis, efficiency, even correctly accounted for, is an important, but not necessarily decisive virtue or criterion. Cost and other intangibles (safety, reliability, environmental impact) must be taken into account.

Hydrogen is a costly alternative

Obviously, the future hydrogen economy must be affordable to be worthwhile. At first glance, this appears challenging, given the energetics of energy carriers (e.g. H_2), and the pricing of stock energy resources (e.g. oil and gas). Like electricity, hydrogen will cost more than the sources from which it is made. This is especially relevant if the primary energy source is a competing fuel, such as natural gas. The corollary is that hydrogen will cost more than fossil energy *until* non-fossil energy prices fall below those of fossil fuels in the marketplace.

As geologic exhaustion approaches, fossil fuel prices will eventually rise above carbonless power prices, but until then fossil fuel providers can forestall widespread competition with carbonless power by pricing fossil fuels just low enough (even intermittently) to make investment and development of non-fossil alternatives risky. It is more likely, however, that we will not exhaust the supply of fossil fuels before exhausting our global environment, and over time *public* costs to health, security, and the environment will continue to rise due to fossil fuel extraction, distribution, and use.

The most profound consequence of fossil fuel use is likely that of destabilizing Earth's climate system as CO_2 from fossil fuels is trapped in the Earth's atmosphere for centuries, altering weather, storms, rainfall patterns, and sea level, impacting water supply systems and food production worldwide. While the economic costs of continued CO_2 emissions from fossil fuel use cannot be precisely known, they will be large and global, scaling with economic development, increasing population, and urbanization in coastal areas. Perhaps most importantly, climate change, and its consequences, can take *centuries* to reverse.

Measured against accelerating climate change in an indefinitely fossil-fueled future, the hydrogen economy will be quite affordable, albeit likely more expensive than the private cost of fossil fuels today. Hydrogen generated on-site from ~$0.05/kWh electricity or delivered by pipeline from fossil sources with $50-100/tonne CO_2 capture and sequestration costs will likely cost $3-5/kg H_2. This is energy equivalent to $3-5/gal gasoline, a multiple of current U.S. fuel costs but comparable to prices paid today in the European Union and Japan.

Of course, high hydrogen fuel prices can be counterbalanced by efficient use. An H_2 fuel cell or hybrid vehicle achieving 60-100 mpg equivalent, refueled with fueled with $5/kg H_2, would cost $600-1000/yr, similar to current gasoline vehicles. Fuel cost sensitivity would provide added incentive for fuel cells in commercial trucking for maximum fuel economy. Higher fuel costs for LH_2 aircraft are counterbalanced by reduced wingspan, engine size and maintenance, as well as takeoff weight, distance, and noise. LH_2 is ~3 times lighter than jet fuel (per unit energy), an intrinsic advantage which compounds with intercontinental flight distances, especially if and when increasing 21st Century incomes justify the time savings of supersonic air travel.

In summary, hydrogen can cost moderately more, but still be competitive with fossil fuels by offering superior or unique benefits: cleaner, quieter, lower maintenance, CO_2-free, likely more decentralized, and less vulnerable than today's energy systems to terrorism, inadvertent outages, and natural disasters. While alternatives to H_2 can satisfy certain niches (e.g. perhaps battery electric cars for short trips), H_2 will be an essential affordable alternative to fossil fuels across the breadth of the future energy economy, especially as the capital stock of vehicles and infrastructure become widespread over the next 50 years, and with it both the necessary economic wealth and the need to invest in the highest efficiency energy systems that *eliminate* greenhouse gases from energy use.

The transition to hydrogen will take decades

Some critics point out that energy efficiency policy steps (e.g. CAFE standards, carbon emission standards, hybrid-electric and "plug-in" hybrid vehicle incentives, and renewable portfolio standards (RPS) for utilities) can reduce CO_2 emissions and petroleum use earlier than a transition to hydrogen fuel. This is certainly true. Even the self-described "aggressive" scenario by the National Academy of Engineering [10] foresees mass production H_2 vehicles in 2015, 100% of new vehicles running on H_2 by 2040, with the transition to an H_2-fueled U.S. automobile fleet complete *circa* 2050.

Such long transition times will likely be the case for any alternative fuel, however, as well as almost any change in energy supply technology or end-use infrastructure. Even fossil fuel development (for example in the Arctic National Wildlife Refuge (ANWR)) can have lead times of up to a decade. High efficiency hybrid gasoline vehicles have been marketed for 5 years and still only account for ~1% of automobile sales. Transitions from today's energy system will take time. The question is what path to follow given this reality.

While efficiency improvements (especially in end-use) have rapid impact, efficiency alone is structurally incapable of *eliminating* CO_2 emissions and/or petroleum use. Efficiency improvement is relatively quick, easy, and cheap (financed by fuel savings) but also, fundamentally, a half-measure. Higher efficiencies reduce (marginal) costs and can increase demand for energy services. Following the introduction of Corporate Average Fleet Fuel Economy (CAFE) fuel economy standards, U.S. automobile fleet on-road fuel economy improved 25% (from 16 to 20 mpg) between 1980-1990. Miles per vehicle grew 20% over the same time frame. Petroleum consumption of U.S. cars has been flat since 1980, with growth in petroleum consumption shifting to pickups, mini-vans, and SUV's (with lower fuel economy) over the last two decades (partly in response to CAFE standards).

Similar outcomes are possible for future efficiency improvements. The U.S. Energy Information Administration (EIA), for example, projects substantial increases in electricity and transportation demand out to 2025. The National Academy of Engineering study mentioned earlier, while foreseeing a 35 year H_2 transition (2015-2050), also estimates annual driving will grow from 12,500 to 20,000 miles per vehicle over the same timeframe.

Ultimately, improving vehicle fuel economy and electric generation efficiency, or mandating renewable portfolio standards can reduce the growth of and perhaps even stabilize CO_2 emission *rates*. A fundamentally different global energy system will be needed to stabilize atmospheric CO_2 *levels*.

Stabilizing atmospheric CO_2 and the climate system requires CO_2 emissions to ultimately fall below ~7 billion tonnes CO_2/yr (1/3rd of present emission rates and 1/6th of projected 2050 emission rates). This is less than 1 tonne of CO_2/yr per person on a global *per capita* basis or roughly 20 times lower than *present* U.S. *per capita* emission rates. For perspective, consider that (approximately) 1 tonne of CO_2 is released to the atmosphere by *each* of the following: a roundtrip cross country airline flight, driving a 100 mpg automobile 30 miles daily, or one year of television viewing or desktop computer use. Clearly efficiency improvements alone will not produce sufficiently deep CO_2 reductions. Future energy systems will need to become essentially carbonless.

The pace at which carbonless energy will be needed can be estimated (albeit imprecisely) by combining climate models and future energy demand projections. Using the IPCC midrange value for climate sensitivity (+3°Celsius for a doubling of preindustrial atmospheric CO_2 burden) and IS92A scenario for energy use, a shift in global primary energy to 80% carbonless power (from today's 80% fossil fuels) within ~ 50 years is necessary just to hold future warming to a global average of perhaps 2°C [18].

In summary, the hydrogen transition will take several decades, but in this strategic context, very long transition times (i.e. ~50 years) for fundamental changes in energy technology make the case for action rather than delay. Delay locks in future CO_2 emissions and petroleum use, increasing our vulnerability to CO_2 induced climate change. Efficiency improvements should be the first action taken, hopefully buying the time to fashion viable, cost effective, and desirable zero carbon energy systems that can be globally deployed. Beyond rapid action to improve efficiency, the decades needed for the transition from petroleum to any alternative argues *for* H_2, not against it. By mid-century, perhaps even earlier, stabilization of Earth's atmosphere and climate system will require mature technologies and refined, consumer-friendly markets for H_2 fuel. As the only chemical fuel that can be clean, carbonless, and universal across all transportation modes, and producible on the scale of global demand, H_2 will be a necessity in the future.

4. ***Hydrogen technologies are immature***

We agree with criticisms that the full range of H_2 technologies is not yet technically mature and therefore commercially ready to support H_2 as a global energy carrier and transportation fuel. Mass producible designs, reduced capital costs, improved efficiency, and high levels of safety will all be needed to bring the hydrogen economy within global reach. No new technologies need to be invented, but there is substantial room for technological advance to make hydrogen vehicles far more valuable to consumers, and refueling infrastructure more attractive to investors.

Future hydrogen economies will differ substantially from the current hydrocarbon economy if for no other reason than the dramatically different physical properties, requirements, and opportunities that arise from producing, storing, and using hydrogen. H_2 will likely be mankind's final chemical fuel. Time should be taken to insure we begin down transition path(s) which are flexible and can evolve in response to (and perhaps accelerate) greater scientific knowledge, technological advance, structural economic change, and shifts in societal attitudes.

Of the necessary technologies, H_2 production is the most mature. Since the discovery of hydrogen as an element of water over 200 years ago, hydrogen has been produced from water using coal or electricity. For the last 50 years large scale steam reforming of methane (natural gas) has been the approach of choice. Reforming is relatively capital and energy efficient (60-70%), best suited to producing hydrogen as an industrial chemical commodity *where it is used* (e.g. a refinery or ammonia synthesis plant). The economic advantage of reforming diminishes once hydrogen must be distributed to fuel stations. This is especially likely to be true early in the transition when hydrogen fuel demand will be insufficient to justify pipelines from centralized H_2 production centers.

An alternative decentralized energy infrastructure can be envisioned, in which hydrogen is produced initially by reforming at the filling station and/or electrolysis at the fleet or even garage scale. But hydrogen production at these scales (and at higher efficiency) is only at the conceptual and/or prototypical development stage, not yet refined for maximum economic value and safety in a retail consumer setting.

Compared to production, distribution and storage of hydrogen have matured only relatively recently. While there are a number of small hydrogen pipelines with substantial operational experience, limited demand results in typical hydrogen distribution by truck as a compressed gas or cryogenic liquid (LH_2). Noting that natural gas is not delivered by truck, one can surmise this approach is relatively expensive in the fuel delivery context. Trucking compressed H_2 gas is capital intensive due to the weight limitations of heavy vessels strong enough to withstand high pressures. Lower pressure and therefore lighter tanks with cryogenic insulation enable a truck to carry ~10 times more hydrogen in the form of LH_2. Unfortunately, liquefying H_2 is currently inefficient and energy intensive, requiring 30-40% of the energy value of H_2 fuel. Another challenge is that LH_2 boils far more easily than liquid natural gas (LNG) or other cryogens. While LNG tankers (ships) and terminals are commercial reality projected to be on the rise, there exist only conceptual analyses of LH_2 tankers.

The technologies for storing hydrogen *onboard* vehicles are even less mature, yet probably most critical to consumer acceptance. The intrinsically low energy density and special conditions of hydrogen storage (e.g. cryogenic temperatures, high pressures) present challenges, especially in a retail context. While analogies can be drawn between compressed hydrogen and compressed natural gas (CNG) vehicles, the basis for comparison relevant to consumers is arguably liquid transportation fuels.

Unfortunately, the transportation modes most fundamentally suited for H_2 storage as a cryogenic liquid (aircraft, ships, and trains) have essentially no current experience base. The LH_2 experience base is historically rooted in spacecraft. More recent experience has developed in refueling and storing LH_2 onboard prototype commercial trucks, and demonstration LH_2 automobiles.

LH_2 storage in relatively small automotive scale vessels has unique challenges. BMW has pioneered automotive storage of liquid hydrogen for 30 years [19], with many demonstrations of storage vessel safety and integrity. A dual fuel (gasoline/LH_2) demonstration fleet of 15 BMW vehicles logged over 100,000 miles in 2003. The fundamental challenge remains keeping LH_2 at temperatures of only 20 Kelvin above absolute zero for *weeks*. Even multilayer vacuum superinsulation (MLVSI) capable of insulating vessels to heat leaks of ~ 1 Watt is insufficient to prevent pressure buildup (100 psi) in LH_2 cars parked 3-4 days, requiring venting of H_2 to relieve pressure. Higher strength pressure vessels are conceptually capable of eliminating H_2 venting. Research at Lawrence Livermore National Laboratory (LLNL) has shown metal-lined composite pressure vessels can withstand cryogenic cycling with LH_2 over an automotive lifecycle with no ill effects. A hydrogen pickup truck with an onboard cryogenic pressure vessel has also been demonstrated, but adapting cryogenic insulation to high pressure vessels is still under investigation [20].

Automakers' recent prototype fuel cell automobiles have relied chiefly on compressed H_2 storage. Arguably the most mature approach to onboard automotive storage, H_2 pressure vessels have become far more practical as the strength of fiber composites has made increasingly higher gas pressures (e.g. 10,000 psi) conceivable.

A less mature option, but with potential safety and stability advantages, is solid state storage in metal hydrides. Metal hydride storage has been studied since the 1970's with limited demonstrations. Recent material breakthroughs with lightweight metals ($NaAlH_4$) offer promise. Even lighter carbon-based hydrogen storage materials (e.g. single-walled nanotubes) are at the basic research stage where the fundamental storage process is controversial and not yet well understood.

No matter what storage technology(s) are ultimately employed onboard H_2 vehicles, driving range will be limited by the intrinsically low (energy) density of hydrogen. Even LH_2 has only _th the energy of an equal volume of gasoline. This gap virtually requires H_2 vehicles to achieve 60-100 mpg equivalent fuel economy for driving ranges of 300-500 miles. Such fuel economies can be approached with hybrid technology and higher efficiency engines, but the highest possible efficiencies will require low cost ($50/kW) automotive fuel cells with ~5000 hr life. These goals have not yet been met, though fuel cell development has accelerated dramatically in the last 5 years. At present, one could reasonably conclude fuel cells, especially for automotive use, are the least mature among hydrogen production, storage, and utilization technologies.

The Road Ahead

The scale and shape of the hydrogen economy the world will move to over this century will depend on a variety factors, both known and unknown. However, the major hydrogen economy archetypes and their key assumptions can be outlined. At least four major archetypes of hydrogen economy exist based on *1)* whether H_2 is produced from fossil energy or carbonless power, and *2)* whether H_2 is produced at or near the point of use, or in large centralized plants and distributed to demand centers.

Archetype 1: Centralized H_2 from Nuclear Power
This is the hydrogen economy as conceptualized in the early 1970's [2-3]. Nuclear fission was the only economic source of carbonless power and was expanding quickly, while oil, capital, and natural gas were still cheap. The U.S. economy was electrifying very quickly and new *electric* transmission and distribution lines were thought to be the chief

constraint to increasing energy use and economic development. It was envisioned that H_2 could instead be pipelined, distributing energy from distant nuclear plants far more economically than electricity over wires, while offering air pollution and other environmental advantages over fossil fuels.

Three trends have substantially altered the rationale for a nuclear hydrogen economy. Today, after the seemingly permanent price increases following the oil shocks, nuclear plants can produce electricity more profitably and efficiently than H_2 (and prevent more CO_2 emissions). In addition, wind and solar power costs have declined dramatically since the 1970's, offering commercial carbonless alternatives to nuclear power. The third trend is the decreasing public acceptance and confidence in nuclear waste disposal for nuclear power plants.

As future electricity generation is increasingly decarbonized by renewables and/or nuclear power, and presuming nuclear waste and public acceptance issues can be overcome and/or if nuclear fusion becomes commercial, nuclear energy will have unique utility in the H_2 economy. As a reliable, economic, and high density carbonless energy source, nuclear H_2 production is synergistic with large scale H_2 liquefaction or industrial operations such as carbon free NH_3 synthesis for fertilizer. Carbonless LH_2 production at or near airports from nuclear plants (potentially underground) would be an attractive way of delivering enormous quantities (up to 20 GW equivalent or 10,000 kg LH_2/minute) of liquid hydrogen while eliminating the need for power lines and/or pipelines. High temperature gas-cooled reactors (HTGR's) under development would be especially well-suited for low cost production of LH_2 by steam electrolysis and/or thermochemical cycles.

Archetype 2: Centralized Fossil H_2 with CO_2 capture

A fossil fueled hydrogen economy may seem counterintuitive, but if carbon (dioxide) capture and sequestration (CCS) technology becomes viable, then reliance on fossil sources of primary energy could continue throughout the 21st Century, with electricity and hydrogen as carbonless energy carriers. Given the supply constraints, higher energy cost, and lower carbon content of oil and gas, it is likely coal will be the dominant CO_2 source in a future fossil hydrogen economy.

Since coal gasification efficiency is not Carnot-limited (unlike electricity generation or nuclear H_2 production) coal gasification can produce H_2 more efficiently and at lower cost than electricity, even more so if CO_2 is to be captured and sequestered. Consequently, whether to produce H_2 or electricity from coal in a CO_2 reduction context, is more of an open question than for nuclear power. Especially when electricity from nuclear and renewable energy is likely to be competitive if not cheaper than electricity from CCS coal power plants.

Ironically, the CCS hydrogen economy of 2030 may resemble the nuclear hydrogen economy envisioned in the 1970's. Pipelining H_2 to points of use should be more economic than transmitting and distributing electricity from centralized coal plants. The key question will be whether the delivered H_2 will be more valuable as transportation fuel or efficient distributed electricity and heat (co)generation using fuel cells. The high duty cycle of stationary electric generation mean that fuel cell capital costs are more easily withstood in the distributed generation market than in automobiles.

A key technology for the fossil hydrogen economy will be pipelines, both for H_2 and CO_2 transport. One issue would be reducing the economic scale of pipelines, to allow an earlier transition from other H_2 sources. Another is the degree to which existing natural gas pipelines could be used, and how to complete the potential changeover from natural gas distribution to H_2. Finally, the low energy cost of coal is particularly helpful to LH_2 for aircraft and distribution by truck. Vehicle driven demand for LH_2 could provide an earlier market for H_2 from coal with CCS until pipelines are justified. The most critical technology for the fossil H_2 economy is CO_2 sequestration. Without it, a fossil H_2 economy could easily generate more greenhouse gases than would be saved by replacing petroleum or natural gas with hydrogen.

Archetype 3: Decentralized H_2 from natural gas

The Rocky Mountain Institute has proposed a hydrogen transition strategy [9] which capitalizes on the advantages of H_2 fuel cells for distributed cogeneration of electricity and heat, while utilizing the existing natural gas pipeline infrastructure to eliminate the need for substantial electricity transmission and distribution upgrades. Hydrogen atoms account for ~ 2/3 of the energy content of natural gas (CH_4). Ultra-efficient reforming of this natural gas to hydrogen while coproducing electricity and heat keeps CO_2 emissions and fuel costs low, allowing high efficiency (~50-60%) stationary fuel cells to compete with grid electricity. Variations in electric demand would allow surplus H_2 storage for delivery to vehicles early in the transition without the infrastructure requirements of a centralized fossil or nuclear hydrogen economy, or the costs of electrolytic hydrogen from wind or solar power. High efficiency (□=60%) fuel cell autos could deliver peak power to the grid when parked, reducing the need for central station electric generation. Overall electric reliability would dramatically improve given the very large numbers of stationary and/or automotive fuel cells available.

Efficient (□~75%) small scale reformers and fuel cells will be key to a decentralized fossil hydrogen economy. Distributed fuel cells would avoid transmission lines and losses, while providing heat for space and water heating, saving the direct use of natural gas and making it available for reforming to generate H_2 for vehicles. This high level of system efficiency would permit a cost-effective transition to be undertaken without increasing overall energy demand or CO_2 emissions.

Affordable natural gas prices (<$6/GJ), successful fuel cells and very successful fuel cell automobiles, most likely with compressed H_2 storage, are all key assumptions to this scenario. In the intermediate term, natural gas supplies may become a limiting factor. Ultimately, since CO_2 is still released into the atmosphere in the decentralized fossil hydrogen economy, it at best serves as forerunner to a more permanent hydrogen economy archetype.

Archetype 4: Decentralized H_2 from Renewables

The renewable H_2 economy has been envisioned since at least the early 1970's [4-7] but grown substantially more viable in the last 10 years as renewable electricity costs (especially for wind) have declined. The central thrust of this archetype is that, since H_2 is far cheaper and easier to store than electricity in distributed but cumulatively large quantities, a natural synergy exists between H_2 and intermittent renewable power sources.

When solar or wind power levels are high, excess electricity would generate H_2 by electrolysis, for direct use as fuel and/or in fuel cells for power during cloudy or windless days and nights. These functions can be conceptually combined, reducing costs, and sharing capital investment, if fuel cell automobiles are available to generate back-up power for homes and distribution back onto the electric grid. A decentralized renewable hydrogen economy can be thought of as the inverse of the decentralized fossil archetype. Rather than consume hydrogen in fuel cells to produce electricity (and heat), electricity would be consumed in electrolyzers to produce hydrogen (and heat).

The greatest challenge to renewable hydrogen will likely be cost for a long time to come. The costs of a renewable hydrogen economy are fundamentally driven by the capital investment necessary to generate and/or distribute renewable energy, which in turn is determined by not only how efficiently the energy is generated, but used also and stored. Synchronizing the daily, weekly, and seasonal variations in supply, storage, and demand for electricity, hydrogen, and heat, both for buildings and vehicles, and across geographies, will be complex, but necessary to achieve the lowest cost renewable H_2 economy.

Though synchronization is likely to be substantially eased by the future possibilities of ubiquitous information technology. Future energy markets will also need to evolve to reflect (and respond to) the real-time costs of energy services. The greatest efficiencies to be gained by a renewable hydrogen economy could lie in allowing consumers to intelligently evaluate energy choices not only about the quantity of energy services they demand, but their quality, timing, intensity, and duration. Real-time electricity prices will probably vary more than electrolysis efficiencies in the future, for example. Consequently operational flexibility of hydrogen technologies within overall systems is likely to be more critical than raw technical performance in a future decentralized renewable hydrogen economy.

Conclusions

While a H_2 economy provides air pollution, energy security, and other energy system benefits, it will be stabilizing global climate that makes the transition from fossil fueled transportation a necessity. Whether produced from nuclear power, renewable energy, fossil fuels with carbon sequestration (or probably a blend of each), H_2 is the only carbonless alternative capable of being universally deployed across all transportation modes on the burgeoning scale of future global energy demand. In the long term, electrolytic H_2 enables solar, wind and nuclear power to simultaneously replace fossil electric generation and power transportation worldwide, synergistically buffering fluctuations in electric demand from the supply variations in carbonless power sources.

Producing and storing H_2 will entail an energetic (and consequently economic) premium, but this can be offset by efficient utilization, and/or coproduction of heat and power in many cases. Nevertheless, H_2 will cost more than fossil fuels, though this can be counterbalanced by the technical potential of H_2 automobiles, trucks, and aircraft for higher fuel economy.

Though no new technologies need to be invented for the hydrogen economy, much more development and experience in hydrogen vehicles of all types will be needed. Advancing the electrochemistry of electrolyzers and fuel cells, improved pressure vessel materials and cryogenics will all substantially improve the performance of the future hydrogen economy.

Whether H_2 generation is centralized or decentralized, using fossil or non-fossil energy sources will determine the need for new large scale energy distribution infrastructure such as pipelines, power lines, tankers, and refueling stations. In particular, if CO_2 capture and sequestration proves viable, H_2 from coal can replace fossil fuels for some time, but dramatic expansion of new H_2 distribution infrastructures will be necessary.

If, however, the uncertainties of CO_2 capture and sequestration are not resolved, we will need to move forward swiftly and methodically deploying the most carbon efficient technologies at hand, and prepare for a hydrogen transition in earnest, as our knowledge of climate change, fossil fuel supplies, future energy demand, and the limits to efficiency grows.

The fundamental question regarding the global hydrogen economy is not so much if, but *when*. The transition from today's fossil fuel economy will, like energy transitions to date, take 30-50 years. Given that, at the moment, we don't know the amount of time available, but we do know that climate stabilization will make the H_2 economy an eventual necessity, it is difficult to find the wisdom in delay.

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